ONE-DIMENSIONAL SIMULATION OF PERPENDICULAR COLLISIONLESS SHOCK WAVE

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1. Introduction

The hybrid numerical simulation is widely used [1-5] to study collisionless shock waves (CSW). Principal mechanisms responsible for the perpendicular CSW structure are ion gyration and anomalous plasma resistance due to development of current instabilities. CSW in plasma with two ion species was studied in [6] taking into account the electron dispersion, but without the ion gyration.

In this paper we study CSW with initial small β taking into account anomalous resistance in one-dimensional approach primarily concerning about the relative role of electron and ion heating and ion distribution function.

2. Setting up the problem

The plasma flow is assumed one-dimensional and occurred across the magnetic field in the axis x direction. We study CSW in the time-dependent formulation assuming that at $x = 0$ there is a perfectly conducting rigid piston which initially homogeneous plasma flows on at velocity $-u$. Take the following for the units: plasma initial density n_0 for density, initial magnetic field B_0 for magnetic field, initial Alfvén velocity for velocity, and c/ω_{pi} for coordinate, where ω_{pi} is initial ion plasma frequency. At the initial time plasma is assumed cold, so that $\beta_{e0} = 0$, $\beta_{i0} = 0.01$.

We assume that the magnetic diffusion coefficient κ and electron thermal conductivity χ are small, taking $\kappa = 0.2$ in the accepted system of units and $\chi = 1.5 n \beta_e \kappa$.

3. Calculation results

Fig.1 shows the ion distribution in the phase planes $x - v_x$, $x - v_y$ (v is ion velocity), magnetic field profile and ion velocity distribution functions ($\frac{v^2}{2} f(v)\,dv$ - fraction of kinetic energy in the velocity interval dv) downstream the front at time $t = 10$ for u = 3 (super-critical shock, the Alfvén-Mach number $M_A \cong 4.4$). The CSW super-criticality is observed on the phase planes (the reflected ions are distinctively seen), on the magnetic field plot (the profile $B(x)$ has a foot and a forward peak related to reflected ions and is of oscillating structure downstream the front), and on the ion distribution function where a group of ions is seen which experienced reflection at the front and, despite a small fraction of the ions, made the major contribution to the ion thermal energy downstream the front. In the computations the profiles vary with time, so that the wave propagation is of a pulsed character.

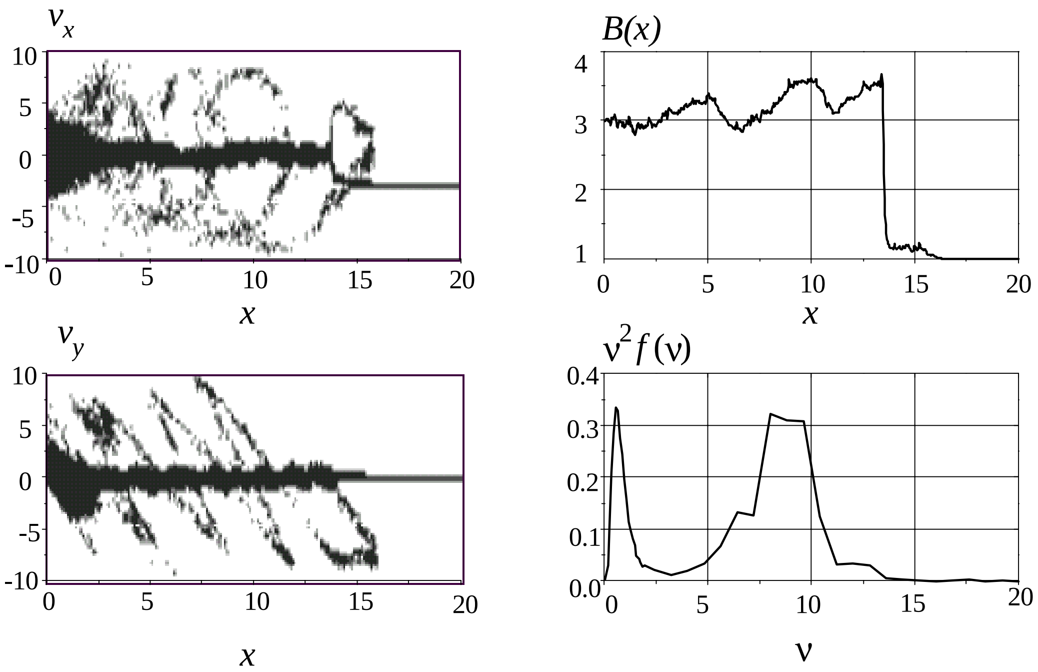

Fig. 1.

The computed data characterizing the plasma status downstream the CSW front is given in the table which presents the following for various velocities u ($u = 1$ - subcritical, $u = 3;6$ - supercritical):

- the computed Alfvén-Mach number estimated by the wave front coordinate;
- the average magnetic field $\overline{B}_1$ downstream the front;
- fractions of internal energy in plasma downstream the front distributed by various degrees of freedom: electron thermal energy W_e , ion thermal energy W_i , energy within the magnetic field oscillations downstream the front W_B ;
- ion velocity downstream the front corresponding to the median kinetic energy (velocity halving the area under the curve $v^2 f(v)$).

U	M_A	$\overline{B}_1$	W_e (%)	W_i (%)	W_B (%)	v_m
1	1.95	2.05	84.7	15.3	0	0.33
3	4.35	3.18	78.7	21.1	0.2	8.2
6	8.46	3.23	52.7	46.7	0.6	13
1, D/T	1.96	2.04	73.4	11.1/15.3	0.2	0.48/0.42
3, D/T	4.45	3.01	55.5	31.5/12.5	0.5	7.5/1.6

The table shows that the ion heating fraction increases with increasing velocity u and Mach number and is about a half for $u = 6$. The obtained ion spectrum proves enriched in "superthermal" particles for all super-critical CSW. Thus, for example, the ratio of median kinetic energy $\frac{m_i v_m^2}{2}$ to average "thermal" energy of ions downstream the front is 42 for $u=3$. The high contribution of the "superthermal" ions to thermal energy downstream the front agrees with the explanation of the DD reaction neutron spectra broadening given in [7].

At the same problem formulation computations were conducted for CSW with two ion species differing in mass by a factor of 1.5 (as applied, e.g., to DT plasma) and of an identical initial concentration.

The computations showed that for subcritical $u=1$, like in the problem with one ion specie, there are no reflected ions and the CSW structure is stationary. However, behind the resistive front gyration of various ion species about the common center of mass starts and a two-flow motion periodic in the front system forms. The two-flow motion instability manifested itself not very severely in the computations.

Fig. 2 shows the ion distribution in the phase planes $x-v_x$, $x-v_y$, magnetic field profile and ion velocity distribution functions downstream the at time $t=10$ for the super-critical mode $u = 3$ (curve D - light ions, curve T - heavy ions). Fig. 2 demonstrates the ion reflection at the front, with the reflection being experienced only by the lighter component, while the heavier is on the phase plane entirely inside the smeared beam which has passed. Also, in the ion distribution there is a large (principal in energy) fraction of superthermal ions in the light component.

The last two rows of the table present computed CSW with two ion species. As the table shows, for these u the ion heating fraction is about twice as high as that in the case of one component.

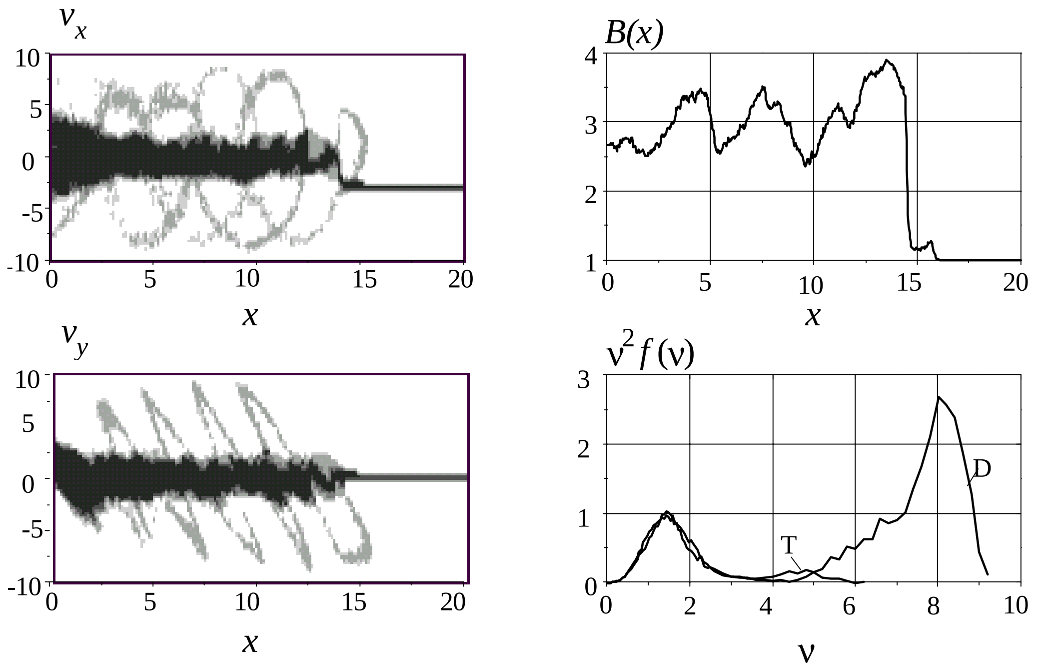

Fig. 2.

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